

SUMMARY OF SESSION 2: HIGH INTENSITY EFFECTS*

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Abstract

The CARE-HHH-APD workshop LHC-LUMI-05 on “Scenarios for the LHC Luminosity Upgrade” was held in Arcidosso, Italy, from August 31st to September 3rd, 2005. The workshop was organized in four plenary morning sessions supported by afternoon sessions of two parallel working groups on LHC IR Upgrade and High Energy Injectors. In this report we review the presentations and discussions in Session 2, devoted to High-Intensity Effects, emphasizing the suggestions for future studies and pointing out the open issues.

INTRODUCTION

There were four presentations on High-Intensity Effects in the LHC and its injectors, addressing the need/advantages of upgraded high energy injectors based on fast super-conducting synchrotrons and including a possible new booster in the ISR or SPS tunnel and a 1 TeV super-SPS with new transfer lines to the LHC:

- Frank Zimmermann—Progress of beam-beam compensation schemes [1],
- Elena Shaposhnikova—High brilliance and closer bunches from the LHC injectors [2],
- Joachim Tuckmantel—New RF systems for the Super-SPS and Super-ISR [3],
- Nuria Catalan—Beam collimation and control in the high energy injectors [4].

The presentation by Elena Shaposhnikova included a discussion of the RF upgrades and a tentative estimate of the related cost for different LHC bunch spacings. This was further discussed in the working group on High Energy Injectors and later at CERN: the conclusions are reported in a separate section.

PROGRESS OF BEAM-BEAM COMPENSATION SCHEMES

Different approaches have been proposed to boost the LHC performance:

- Increase crossing angle and reduce bunch length to stay at the beam-beam limit. This requires a higher-frequency bunch shortening RF system and reduced longitudinal emittance.
- Reduce crossing angle and apply ‘wire’ compensation.

- Crab cavities have the potential to go to large crossing angles without luminosity loss.
- Collide long intense bunches with large crossing angle, without exceeding the beam-beam limit.

The two promising schemes of wire compensation and crab crossing were discussed by Frank Zimmermann.

Long-range wire compensation

Frank Zimmermann presented the merits of the wire compensation, underlining that long-range compensation was demonstrated in the SPS using two wires (beam lifetime recovery), simulations predict $1-2\sigma$ gain in dynamic aperture for nominal LHC, and wire compensation allows keeping the same—or smaller—crossing angle for higher beam current with no additional geometric luminosity loss. Challenges and plans include further SPS experiments (3rd wire in 2007), a demonstration of the wire compensation effectiveness with real colliding beams (at RHIC), and the study of options for a pulsed wire.

Simulations of long-range compensation with two wires indicate that the beam lifetime is recovered over a wide tune range but not for all tunes. The measured SPS lifetime at 26 GeV can be fitted by the expression $5 \text{ msec} \times (d/\sigma)^5$, where d is the beam-wire separation and σ the transverse r.m.s. beam size. A naive extrapolation to the LHC beam-beam separation of about 9.5σ would yield a beam lifetime of only 6 minutes! This estimate is pessimistic, since the SPS beam lifetime was very short as a consequence of several noise sources. Tevatron observations with an electron lens show a cubic dependence on the ratio d/σ . Further SPS tests at different energy are needed to validate the energy scaling.

Beam lifetimes predicted by simulation codes are much larger than those observed, even though the sensitivity to machine parameters seems correct. Further understanding and beam tests are needed, e.g. at RHIC.

For extreme PACMAN bunches there is over-compensation which causes the footprint to flip over or to increase instead of shrinking. To avoid degraded lifetime for PACMAN bunches, the wire should be pulsed train by train. It is rather challenging to make a pulsed wire for beam-beam compensation: the required average pulse rate is 439 kHz and the turn-by-turn amplitude stability is 10^{-4} .

Experiments at RHIC (by Wolfram Fischer et al.) with a single long-range encounter show that the beam-beam effect is visible starting from a separation of about 5σ , consistent with Tevatron and Daphne observations, but contrary to LHC simulations and possibly to earlier observations at the SPS collider.

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Crab cavities

Frank Zimmermann presented the merits of crab cavities, underlining that a practical demonstration will be possible at KEKB in early 2006, that crab cavities can avoid the geometric luminosity loss for large crossing angles (no long-range beam-beam effect) and have the potential of boosting the beam-beam tune shift by a factor 2-3, as predicted for KEKB. Challenges and proposed plans include the design and prototyping of a Super-LHC crab cavity (Cornell is interested) and the demonstration that noise-induced emittance growth is acceptable for hadron colliders (possible installation and experiment at RHIC).

For crossing angles above 1 mrad, the required Crab cavity RF voltage is significantly lower than for a bunch shortening RF system. The Crab cavity impedance can be controlled by coaxial couplers or waveguide dampers and by a proper elliptical cavity shape, to shift the frequency of unwanted modes: the instability rise time for a single Crab cavity corresponds approximately to the rise time induced by 10 normal RF cavities with the same total voltage. Moreover, the phase or timing tolerances for Super-LHC crab cavities is about an order of magnitude lower than for KEKB and even tighter than for the ILC.

HIGH BRILLIANCE AND CLOSER BUNCHES FROM THE LHC INJECTORS

Elena Shaposhnikova presented an analysis of the beam performance with the existing LHC injectors and with possible new high energy injectors. The main conclusion is that the SPS is the bottle-neck to reach and exceed ultimate LHC intensity. The target impedance for a Super-SPS is about 0.5Ω , *i.e.*, about an order of magnitude less than the present SPS.

Existing LHC injectors

The main limitation to reach higher brilliance comes from the SPS, where the nominal LHC emittance is not yet reached in the vertical plane owing to electron cloud effects. The limitations associated to closer bunches are a new RF system needed either in the PS (10 or 15 ns) or SPS and LHC (12.5 ns). In the SPS more problems are anticipated with electron cloud (vertical emittance blow-up) and coupled bunch instabilities.

Intensity dependent capture losses in the SPS were reduced in 2004, but their exact cause and therefore scaling is not clear. Coupled bunch instabilities in the SPS can be cured by controlled emittance blow-up. This requires a 200 MHz capture system in the LHC. Beam loading in the 200 MHz and 800 MHz RF systems is a limit at ultimate intensity for known performance. A fast transverse instability is anticipated for more MKE kickers or higher bunch intensities. Below this TMCI-like threshold there can still be emittance blow-up. Curing the TMCI instability by a large chromaticity at high RF voltage may increase the beam losses.

Possible improvements and machine studies include a further SPS impedance reduction, in particular for the MKE kickers, capture loss and beam lifetime SPS studies possibly with shorter bunches from the PS, bunches with ultimate intensity injected into the SPS using PS batch compression, and electron cloud 'scrubbing runs' at higher intensities.

Future LHC injectors

The present SPS could be used as a booster ring injecting at 150 GeV into a new Super-SPS (to be named Hyper-PS or HPS) located in the same tunnel and reaching 1 TeV. Reducing the top energy in the SPS to 150 GeV allows the ramp length to be reduced to 2 s, but does not improve the coupled-bunch longitudinal beam stability on the flat top (*i.e.*, a controlled blow-up of the longitudinal emittance may still be necessary) and makes more difficult bunch-to-bucket transfer into the 400 MHz RF system of the next ring.

With the present SPS and pre-injectors, the minimum ramp length of the HPS can be 6 s. Using a 400 MHz super-conducting RF system requires an extra capture RF system and twice more voltage than with the 200 MHz system. Using a 200 MHz normal conducting RF system seems to be optimal, but requires a tight impedance budget of $Z/n < 0.5 \Omega$ probably achievable for a new machine.

RF UPGRADES FOR DIFFERENT LHC BUNCH SPACINGS

Electron cloud effects may exclude the possibility of reducing the LHC bunch spacing below its nominal value. Any bunch spacing shorter than 25 ns requires new electronics for the LHC BPM system, upgraded feedback systems, RF couplers, collimation, cryogenics, beam dump, etc. A tentative cost estimate for the *difference* between the two options of 12.5 ns and 10-15 ns bunch spacing is shown in Table 1 and amounts to about 30 MSfr. This does not include accelerator equipment upgrades common to the two options and should be compared to the corresponding cost difference estimate from the LHC experiments.

There are two possibilities for a reduced bunch spacing of 12.5 ns:

- A new low-frequency RF system in the SPS and a capture RF system at the same frequency (*i.e.*, 160 or 240 MHz) in the LHC. This is the option reported in Table 1.
- A new high-frequency main RF system (320 or 400 MHz) and a capture RF system (160 MHz) in the SPS. No capture RF system in the LHC.

The total cost would be about the same, but it could be distributed differently between SPS and LHC.

Table 1: Additional RF equipment needed in the LHC and its present injectors and tentative cost estimate for the *difference* between the two options of 12.5 ns and 10-15 ns bunch spacing.

| 12.5 ns bunch spacing | | | |
|----------------------------------|--|--|------------------|
| | PS: double RF voltage at 80 MHz | | ~ 2 MSfr |
| | SPS: more RF power and new RF cavities at 160 or 240 MHz | | ~ 35 MSfr |
| | LHC: new capture cavities at 160 or 240 MHz (2×3 MV) | | ~ 25 MSfr |
| | TOTAL (12.5 ns) | | ~ 62 MSfr |
| 10 or 15 ns bunch spacing | | | |
| | PS: new RF system at 60 MHz | | ~ 5 MSfr |
| | SPS: double RF power at 200 MHz | | ~ 20 MSfr |
| | LHC: more RF power at 400 MHz | | ~ 10 MSfr |
| | TOTAL (10 or 15 ns) | | ~ 35 MSfr |

NEW RF SYSTEMS FOR THE SUPER-SPS AND SUPER-ISR

Joachim Tuckmantel presented a comprehensive review of the RF system requirements necessary to fulfil the desired specifications for the new high-energy LHC injectors and the consequent technical implications. In particular he discussed advantages and disadvantages of travelling wave vs standing wave cavities, comparing normal conducting and super-conducting options.

He remarked that just a few cavities, either copper or super-conducting, can easily supply the desired voltage. The gradients have to be lowered voluntarily, since the power coupler cannot transmit the corresponding RF power to accelerate high beam currents and compensate reactive beam loading. Therefore power coupler capabilities have to be increased considerably by a vigorous R&D effort. For super-conducting cavity couplers, RF losses into liquid He may lead to ‘de-conditioning’.

The existing RF power sources for a 200 MHz system are very space consuming and this creates a problem to house them close to cavities underground to minimize RF feedback delays. There is also a need to study compact RF power transmitters at 200 MHz.

In conclusion:

- RF power generators should be located in the tunnel to reduce feedback delays,
- High power transmitters at or below 200 MHz are drastically different from higher frequency technology (klystrons). Also expertise in super-conducting RF is very different from that in travelling or standing wave cavities. There are good reasons to adopt different technologies for different synchrotrons, e.g. super-conducting cavities have very limited tunability and are not suited for lower energy injectors, however there is also a strong incentive to adopt similar technologies to reduce development and maintainance costs (P+M). This may guide the design of the future LHC injector complex.

BEAM COLLIMATION AND CONTROL IN THE HIGH ENERGY INJECTORS

Nuria Catalan presented some ideas on possible collimation systems for a double ring in the SPS tunnel (a low energy ring with conventional magnet technology to accelerate protons from 26 to 150 GeV, SPS, and a second high energy ring using superconducting magnets to reach 1 TeV, SSPS). The level of tolerable losses is given by three main limitations:

- Heat load (global, superconducting). Not more than 3 W/m uniformly distributed over the ring circumference
- Quench levels (local, superconducting). Maximum beam power deposited in one spot before the magnets quench must be in the range 10-50 W/m.
- Activation and maintenance (local, general). Localized loss power must not exceed 1-10 W/m.

Most of the losses occur at injection, transition crossing and extraction. Identification of the loss mechanisms is a key ingredient for an efficient collimator system design because the collimation efficiency depends on the number of particles at the large betatron amplitudes (halo population) and on the diffusion rate of the particles toward this halo. The worst case scenario consists in considering slow continuous losses.

The type of collimation system depends on the energy of the ring. The amount of power associated to the beam clearly indicates that a collimation system is needed for the high energy ring, whereas for the low energy ring it would only be necessary to avoid excessive activation or at extraction.

- At 25 GeV, the energy loss per impact is sufficient to kick the halo particles out of their buckets for almost any size and material collimators. Besides, particles get significant angular kicks and have a weak nuclear absorption. Collimation can be very efficient within one to few turns.
- At 1 TeV the energy loss and the angular kick per impact are very small for practical size jaws, even considering the heaviest elements. Therefore collimation

would definitely be a multi-turn process. The nuclear absorption can be very close to 100% even for small collimator sizes, but it must be kept below a certain limit due to heating and out-scattering (i.e., particles that leave the jaw before the full traversal, their number decreases with increasing energy). The use of primary short collimators in light material could minimize nuclear absorption while maximizing the angular scattering.

- At 150 GeV the momentum loss and the angular kick per impact are significant but cannot kick the particles out in one passage. Multi-turn cleaning would then require a high momentum acceptance of the machine in order not to randomly lose the particles before they intercept the jaws.

At all energies, particles outscattered from the jaws have to be intercepted by secondary collimators (absorbers) placed downstream. To have a good collimation efficiency, at the low energies the secondary collimators must be put at the right phase advance to absorb the halo particles within one or few turns, whereas at the intermediate and high energy ranges the halo particles may have to circulate many turns in the machine before they hit the absorber, which poses a requirement on the machine acceptance.

Finally, one could think of a collimator system for the double ring that is made of:

- Momentum cleaning at low energy in the SPS. It requires a heavy material scraper and local collimators placed at the right phase advance.
- Protection absorbers in the transfer line.
- Both momentum and betatron cleaning at injection and extraction energy in the SSPS. If possible one could use the same secondary collimators but different primaries for different energies (this would require a special optics design).

REFERENCES

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- [3] J. Tuckmantel, these proceedings.
- [4] N. Catalan, these proceedings.